Machinery Messages

Case History

Torsional vibration damper selection–

high-powered performance boat engine

Torque Engineering of Elkhart, Indiana contracted Bently Nevada to assist with torsional vibration measurement of a high technology, prototype marine engine installed with a viscous torsional vibration damper. Bently Nevada's TK17 enabled them to evaluate and select the optimum, most cost-effective torsional damper which satisfied their performance requirements. *Photo courtesy of Torque Engineering*

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Bently Nevada was recently involved in the measurement of torsional vibrations present in an internal combustion, reciprocating engine application. The engine tested was a 12-cylinder (V-12), large-displacement, performance powerboat engine, capable of 1492 N·m (1100 ft·lb) of torque at 950 hp and 5000 rpm. These engines are designed, developed, and manufactured by Torque Engineering (Elkhart, Indiana) and are used in high-powered watercraft applications worldwide. Torque Engineering contracted Bently Nevada to assist with torsional vibration measurement of a high technology, prototype marine engine installed with a viscous torsional vibration damper. Three different damper types (different viscosities) were tested during a one-day performance dynamometer test at the customer's manufacturing facility.

Torsional vibration: general characteristics

Torsional vibration is a common characteristic of all rotating and reciprocating machines. A rotating machine does not turn at constant angular velocity, even under constant speed conditions. Variations in the speed of the shaft are called angular or torsional vibrations, and variations in the twist of the shaft are produced by torque fluctuations. The severity of torsional vibrations and shear stresses caused by torsional vibration depends on many parameters: operating speed, torsional natural frequencies, lateral natural frequencies and mode shapes of the shaft system, system damping characteristics, and any excitation frequencies produced by torque fluctuations.

Different torsional vibration at different locations implies twisting in the shaft (Figure1). This oscillatory motion is superimposed on the steady rotational motion of the machine and is responsible for the rotor oscillating shear stress-

es. In addition to the torsional motion equations, maximum shear stress τ_{max} (Figure 2), derived from Hooke's Law (due to torsion), is determined by the following equation:

$$\tau_{max} = G\,r\,\frac{(\theta - \varphi)}{L} \qquad (1)$$

where:

$G =$ *shear modulus*
$L =$ *shaft section length*
$r =$ *shaft radius*

If the total torsional angle of twist ($\theta - \varphi$) is measured between two planes, the resultant shear stresses τ can be calculated. For a round shaft, the shear stress is zero at the center and maximum at the surface. Designating r as the radius of the shaft, the maximum stress τ_{max} can be determined.

Aside from the direct excitation by the variable torque, torsional modes can be excited by lateral-to-torsional "cross-coupling." Lateral/torsional coupling occurs through unbalance effects, radial sideloads with rotating asymmetry, gearboxes, crankshafts, etc.

Torsional vibration: the reciprocating engine

Depending upon the application, the amplitude of torsional vibration that occurs can be dangerously excessive, to the point where torsional stress values can exceed shaft yield or fatigue strengths, seriously shortening the life of a machine. In particular, crankshafts which are used in internal combustion reciprocating engines are subject to high torsional vibration. These vibrations are due to the influence of reciprocating forces (pulsations) produced by piston action and to crankshaft profile (mechanical design).

In a reciprocating engine, combustion generates an extremely rapid rise in cylinder pressure that results in a torque spike. The pressure applied to the top of the piston is transferred to the crankshaft through the connecting rod. This force not only causes the crankshaft to turn, but can actually deflect or twist it. The twist and resulting rebound of the crank arm creates the torsional vibrations (Figure 3). The deflection also produces lateral vibration.

In conjunction with this, shaft profile (crankshaft design) has a significant impact on the location and severity of lateral and torsional excitation frequencies. A crankshaft assembly (pistons, connecting rods, and flywheel) will have a particular natural frequency of vibration. If the design is altered, such as removing material or changing the flywheel weight, the natural frequency of the crankshaft may be shifted dramatically. At a particular speed, the frequency of the torque spike (from combustion effects described above) may equal the lateral or torsional natural frequency of the crankshaft, resulting in a lateral or torsional resonance. This is particularly undesirable, as prolonged excitation of a crankshaft natural frequency can result in premature failure.

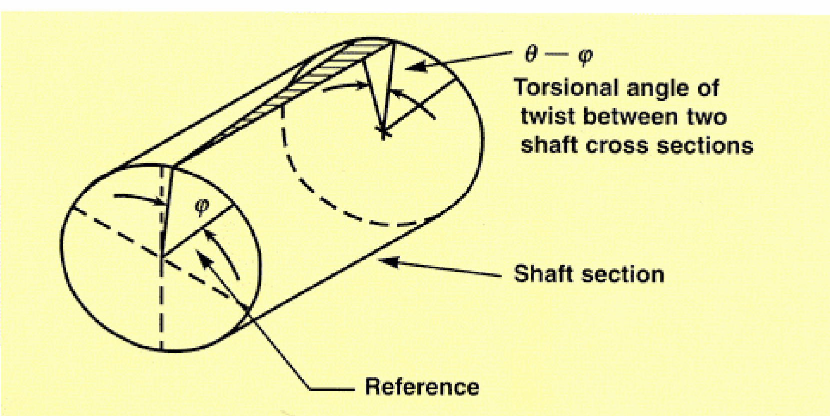

Figure 1
Torsional displacement between shaft cross sections.

Unchecked torsional vibrations can cause:

- Crankshaft cracking or failure
- Excessive bearing wear
- Excessive gear wear or failure
- Broken accessory drives
- Throwing or slapping of belts

Torsional dampers

To minimize the damaging effects of torsional vibrations in reciprocating engines, a viscous damper is often used (Figure 4). The damper construction consists of a free-rotating inertia ring surrounded by a high viscosity silicone fluid enclosed in a sealed, leakproof housing. When crankshaft torsional vibrations occur, the outer housing of the damper reacts with the crankshaft, while the inertia ring moves *out of phase* with the housing. This relative motion between the inertia ring and housing shears the silicone fluid. The nature of silicone fluid results in high energy dissipation, which makes it an excellent damping medium, effectively reducing the torsional vibration.

The torsional damper is press fit and bolted to the front stub-end of the crankshaft, to ensure firm contact with the crankshaft. A positioning key is provided on the damper hub for timing mark position and ease of installation.

Basic measurement, setup, and considerations

Bently Nevada's TK17 Torsional Vibration Signal Conditioner provides a reliable method of measuring torsional vibration. Torsional vibration is measured by using two proximity or optical transducers to observe a reference mounted on the shaft. The reference is usually a precision manufactured gear, which is mounted away from any torsional node. Transducers are mounted in line with the reference gear, 180° apart, and observe the time interval from one tooth to the next (Figure 5).

If the shaft is moving at a constant angular velocity, there is no variation in the tooth-to-tooth timing and, therefore, no angular vibration. If there is torsional vibration, the tooth-to-tooth timing will change. The transducers send the tooth-

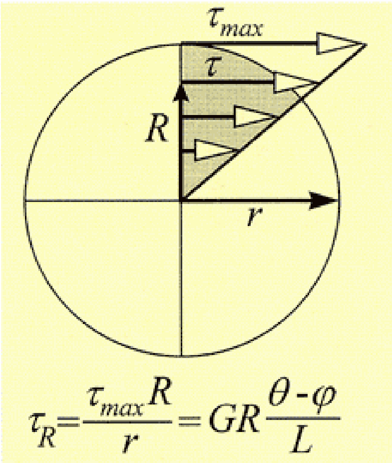

Figure 2
Rotor cross section with Shear Stress distribution.

to-tooth timing signal to the TK17 which will detect these changes.

Certain sources of error must be dealt with before acquiring torsional vibration data. These errors can be introduced from mechanical, machinery, and electrical sources. Always investigate and avoid the following problem areas:

- Gear machining errors, such as pitch circle runout or nonconcentricity, irregular tooth spacing, or tooth profile. Split gears used for reference can also introduce circular pitch error due to the split line, if not properly machined. One-piece, solid precision gears work best.
- Radial (lateral) vibration. This is eliminated by using two transducers 180° apart. Radial vibration is effectively "canceled out" when the TK17 adds the signal from the two transducers.
- Improper transducer selection. The correct size of the transducer is determined by the width of the gear teeth and gap between the top of the tooth and transducer tip. If the transducer range is too small, an inadequate signal may be input to the TK17. If the transducer tip diameter is too large, the electromagnetic field may intercept more then one tooth at a time, also reducing the signal amplitude. In general, for an eddy current probe, the tooth width and spaces between teeth should be at least as large as the probe coil diameter. In addition, the transducer must be carefully gapped in order to generate a pulse amplitude within the operating range of the instrumentation. If necessary, a signal conditioner can be used to "square up" the signal.

For the dynamometer test conducted on the marine engine, a probe pair, mounted 180° apart, was installed at each end of the engine. The damper end (engine-front) probes were oriented at 45° left and 135° right of top-dead-center, and the flywheel end (engine-rear) at 90° left and right of top-dead-center. Bently Nevada 7200 Series, 5 mm tip diameter proximity probes, with an output scale factor of 7.9 mV/μm (200 mV/mil), were connected to the TK17. Output scale factor for the TK-17 was set at 0.5 V/deg. An optical Keyphasor® transducer, installed at the engine rear coupling hub location, was used as a once-per-turn speed reference. Gears used for the torsional measurement included a 40-tooth solid precision gear at the damper end and a 168-tooth flywheel at the opposite end.

Test objective, specifications, and criteria

The purpose of this test was to qualify and select a torsional damper, which performed adequately at the engine's operating conditions, and within the OEM's operating limits. The selected damper would then become the standard configuration for this engine type. Two types of performance tests were conducted in accordance with the engine manufacturer's specifications: a power sweep test and a constant throttle angle test.

During a power sweep test, process variables (such as torque, horsepower, combustion temperature, etc.) are measured versus throttle plate angle (percentage of throttle opening) and speed. This information is then correlated with the damper type and amount of torsional vibration observed. As power is increased, the effect of torsional damping (or lack thereof) is evaluated. Power sweeps show the torsional vibration (overall degrees) for 25° throttle angle/2500 rpm, 35°/3500, 40°/4000, etc.

The constant throttle angle test provides an indication of engine torsional response characteristics with constant power and reduced speed. This condition most closely simulates an engine "cut-out," when the fuel pressure may be lost (such as a ruptured fuel line, etc.), or some other failure which would cause the engine to slow down at a specific power level.

In accordance with the viscous damper manufacturer recommendations, the test criteria, measured as double-angle (degree peak to peak) amplitudes, should not exceed 3.0° pp, regardless of test type.

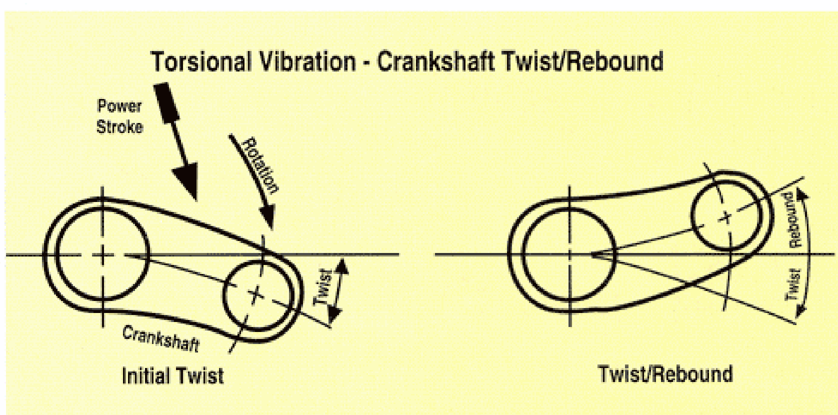

Figure 3
Typical Crankshaft Deflection / Rebound.
Diagram courtesy of Vibratech, Inc.

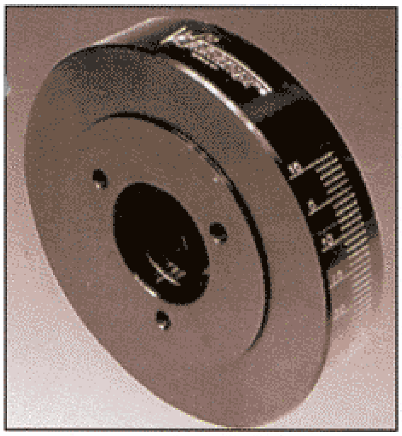

Figure 4
Torsional damper.
Photo courtesy of Vibratech, Inc.

Test observations and results

For this case history, the power sweep test results were more meaningful and are, therefore, presented here. Speed was increased in steps from approximately 2500 rpm to 5300 rpm at full throttle, and torsional measurements were obtained at the damper and flywheel ends. Figures 6a through 6c show the observed damper-end torsional response for the three different dampers used.

The Bode plots (left hand side) show a torsional resonance, or a lateral resonance reflected in the torsional response by cross-coupling, occurring near 3350 rpm for each damper, with corresponding 1X double-angle amplitudes of 0.55 (030 Series), 0.47 (060 Series), and 0.50 (100 Series) degree pp. The resonance is indicated by the maximum double-angle peak accompanied by a 90° phase angle shift. Spectrum cascade plots (right hand side) show the 1X response during the resonance regions, as well as torsional excitation of 1.5X, 2.5X, and 3.0X frequency components.

Note that the data does not divulge whether the resonance is pure torsional or lateral. The exact diagnosis could come from lateral vibration measurements and computer simulation (for example, critical speed mapping, etc.) of the engine dynamic response. Lateral mode vibrations which are transferred to torsional modes can result in very high torsional vibration amplitudes which can increase failure probability.

Process variable conditions at the resonance frequency (3350 cpm) correspond to an approximately 33.5° throttle plate opening, 1280 N·m (945 ft·lb) torque, and 603 hp (for the 060 Series damper). At these conditions, engine peak dynamic torsional stress occurs. Also noteworthy is the moderately low amplification factor; the effect of adding a viscous damper to the engine configuration changes the system dynamic response. The additional damping eliminates a sharp, high amplitude, instantaneous excursion at the torsional resonance frequency. The undamped engine might reveal very high amplification factors at the torsional resonance frequency. Data was not acquired for an undamped engine, but it would be useful for a comparative analysis. A ratio of the damped versus undamped torsional vibration amplitude could then be evaluated for system stiffness quality and individual damper effectiveness.

Observations of the flywheel-end torsional response characteristics yielded no conclusive results; observed double-angle amplitudes were less than 0.05 degree pp for each damper type. The flywheel's chief function is to provide torsional dynamic stiffness to the reciprocating and rotative forces. As expected, the flywheel was not greatly susceptible to these torsional forces. For the system analyzed, damper-end to flywheel-end response differed by a ratio of 10:1.

From these tests, it was determined that the 060 Series damper was best suited for the application, taking into account system torsional stiffness characteristics, power sweep test criteria, engine performance parameters, cost, and damper torsional damping quality.

Conclusions

The customer was able to successfully compare and qualify the torsional damping characteristics of three different viscous dampers for their prototype marine engine. Information provided by Bently Nevada's TK17 enabled the customer to evaluate and select the optimum, most cost-effective torsional damper which satisfied their performance requirements and the damper manufacturer criteria. They will be using the acquired torsional data as a benchmark for future engine design considerations.

This case history provides heightened awareness and insight to the importance of torsional vibration measurements in a special application. Torsional vibration measurements, however, can be useful for analyzing nearly any rotating or reciprocating machine. Synchronous and variable frequency motors, flexible couplings, gear drives, and reciprocating compressors are some examples which often experience high levels of torsional vibration. Excessive torsional vibrations can result in coupling wear, bearing wear, gear wear, gear tooth rupture, key

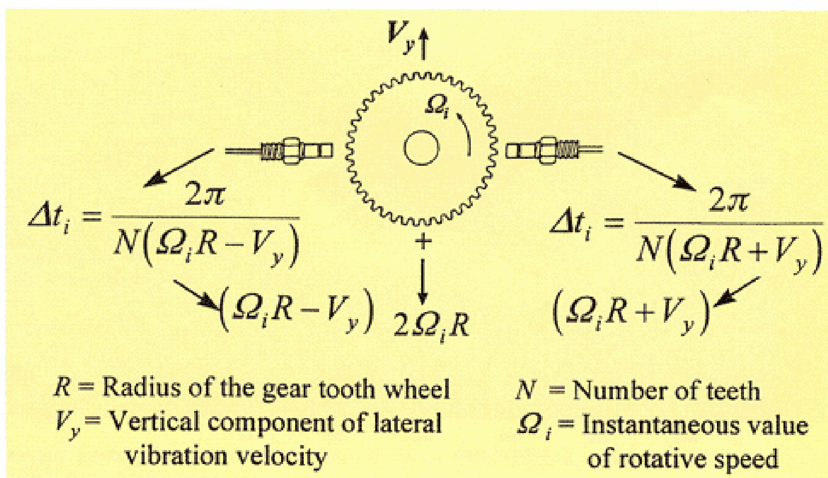

Figure 5
Transducer orientation.

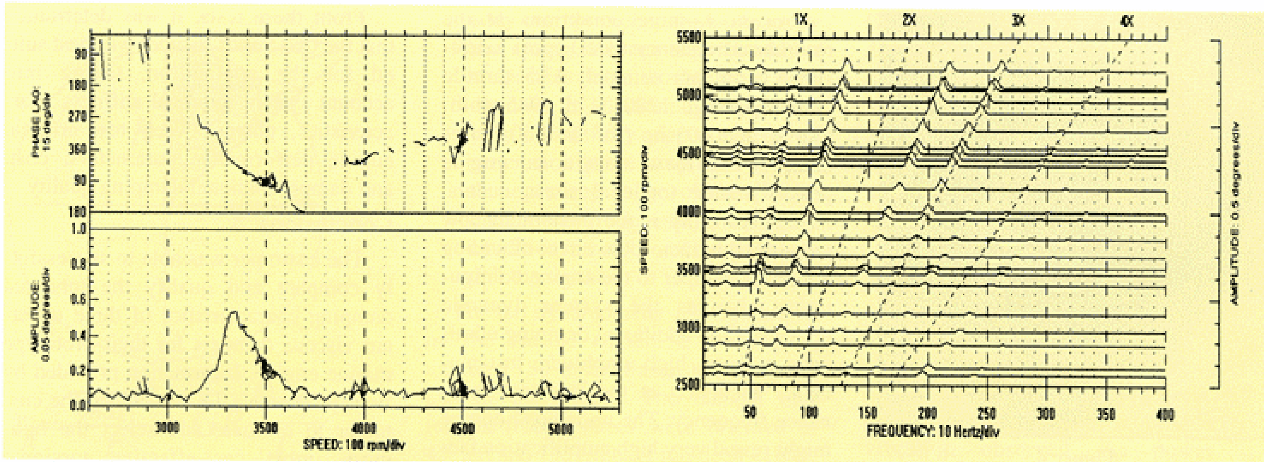

Figure 6a
1X Bode and spectrum cascade plots - Damper end torsional response, power sweep, 030 Series damper.

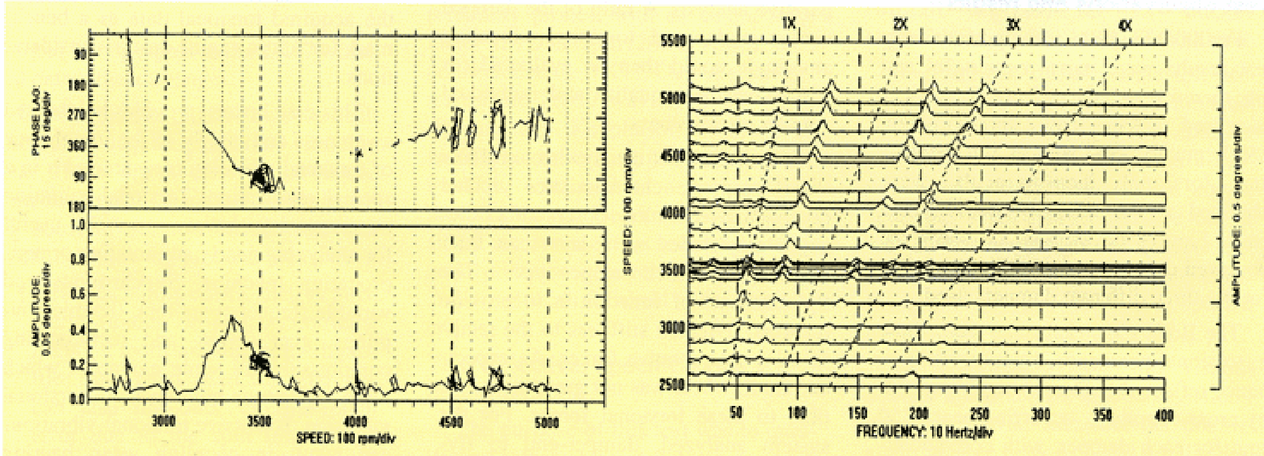

Figure 6b
1X Bode and spectrum cascade plots - Damper end torsional response, power sweep, 060 Series damper.

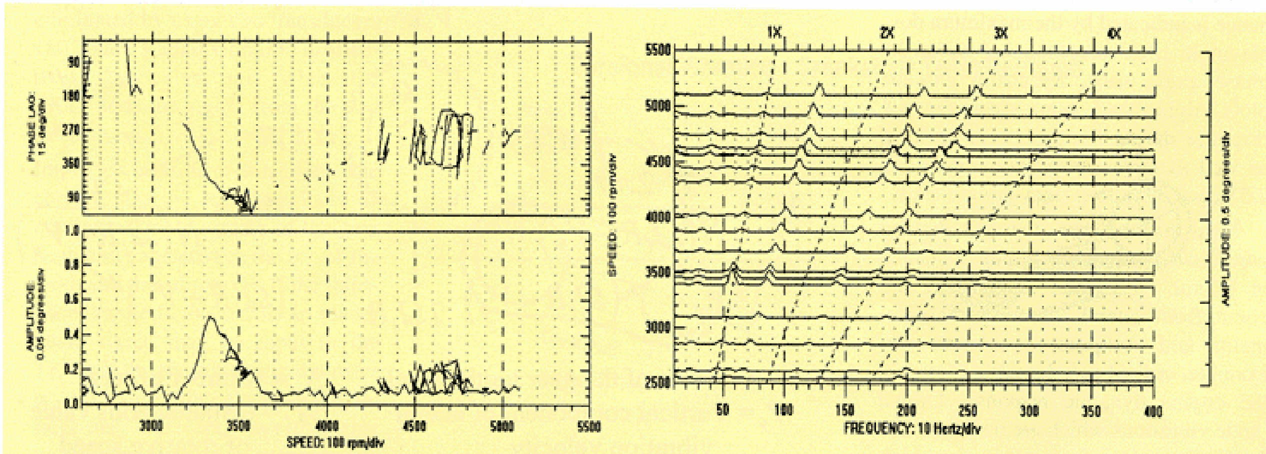

Figure 6c
1X Bode and spectrum cascade plots - Damper end torsional response, power sweep, 100 Series damper.

failures, and cracked shafts. Extremely hazardous and catastrophic failures are associated with broken couplings or cracked shafts. The significance of torsional vibration assessment, carefully evaluated with lateral vibration response and process variable conditions, cannot be overemphasized. The implementation of torsional vibration measurements in a predictive maintenance program would be a very effective way of reducing operational costs and averting unplanned outages.

Bently Nevada can provide a wide array of instrumentation and expertise to assist with torsional vibration measurement and analysis. ADRE® for Windows software, used in conjunction with a 208-P Data Acquisition Interface Unit (DAIU), can accept TK17 signal outputs directly (in proper degree peak to peak units) without further scale factor conversion. In addition, process variable transducers (e.g., temperature, pressure, horsepower, motor current, flow rate, etc.) can also be input to the 208-P DAIU, for real-time trending and correlation to vibration data.

Bently Rotor Dynamics Research Corporation (BRDRC) can offer specialized expertise and the most modern technological resources available in the industry to develop practical solutions to machinery behavior problems. Contact your nearest Bently Nevada Sales Representative for additional information on the resources, capabilities, and availability of Bently Rotor Dynamics Research Corporation.

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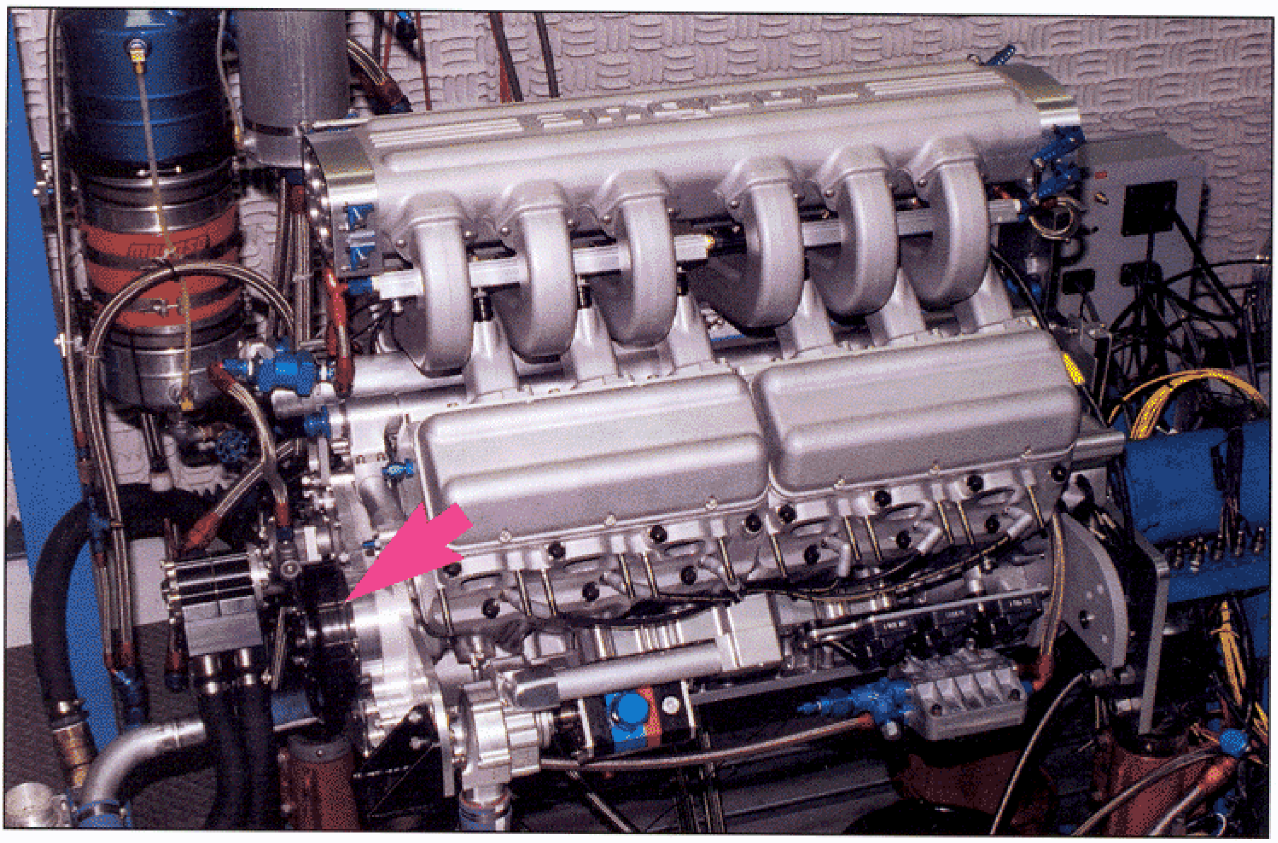

This 12-cylinder (V-12), large-displacement, performance powerboat engine is designed, developed, and manufactured by Torque Engineering (Elkhart, Indiana). It is used in high-powered watercraft applications worldwide. Note the arrow indicating the torsional damper installed on the front-end of the crankshaft. *Photo courtesy of Torque Engineering*